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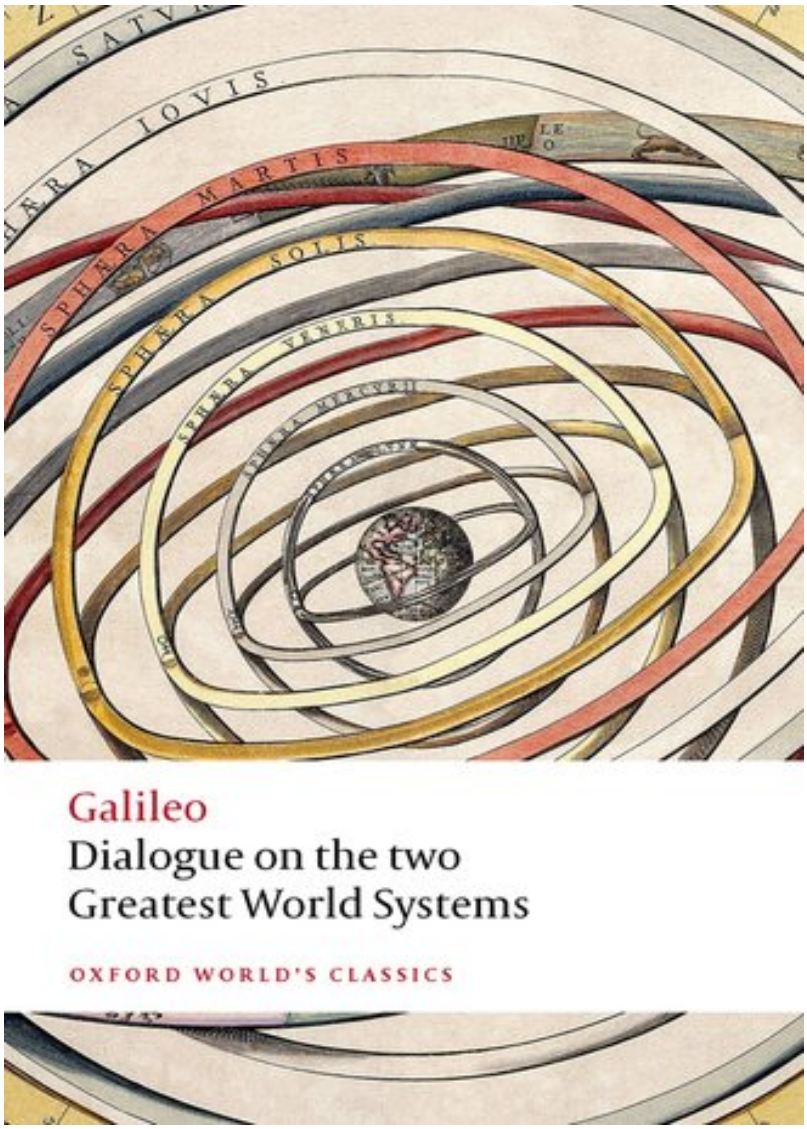

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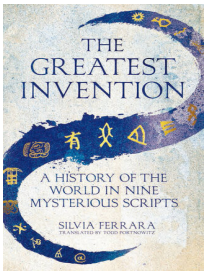

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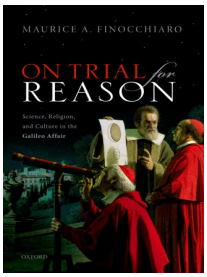

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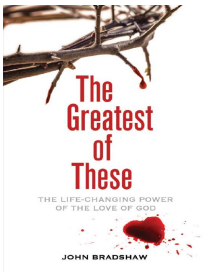

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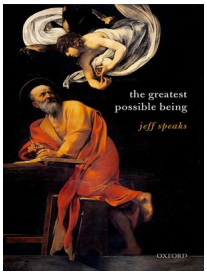

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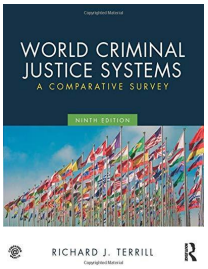

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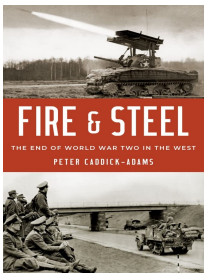

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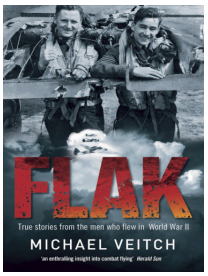

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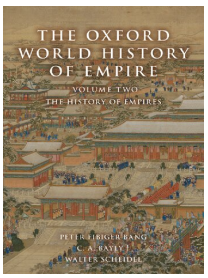

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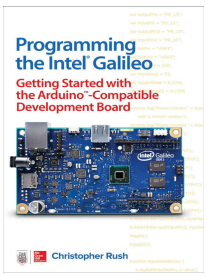

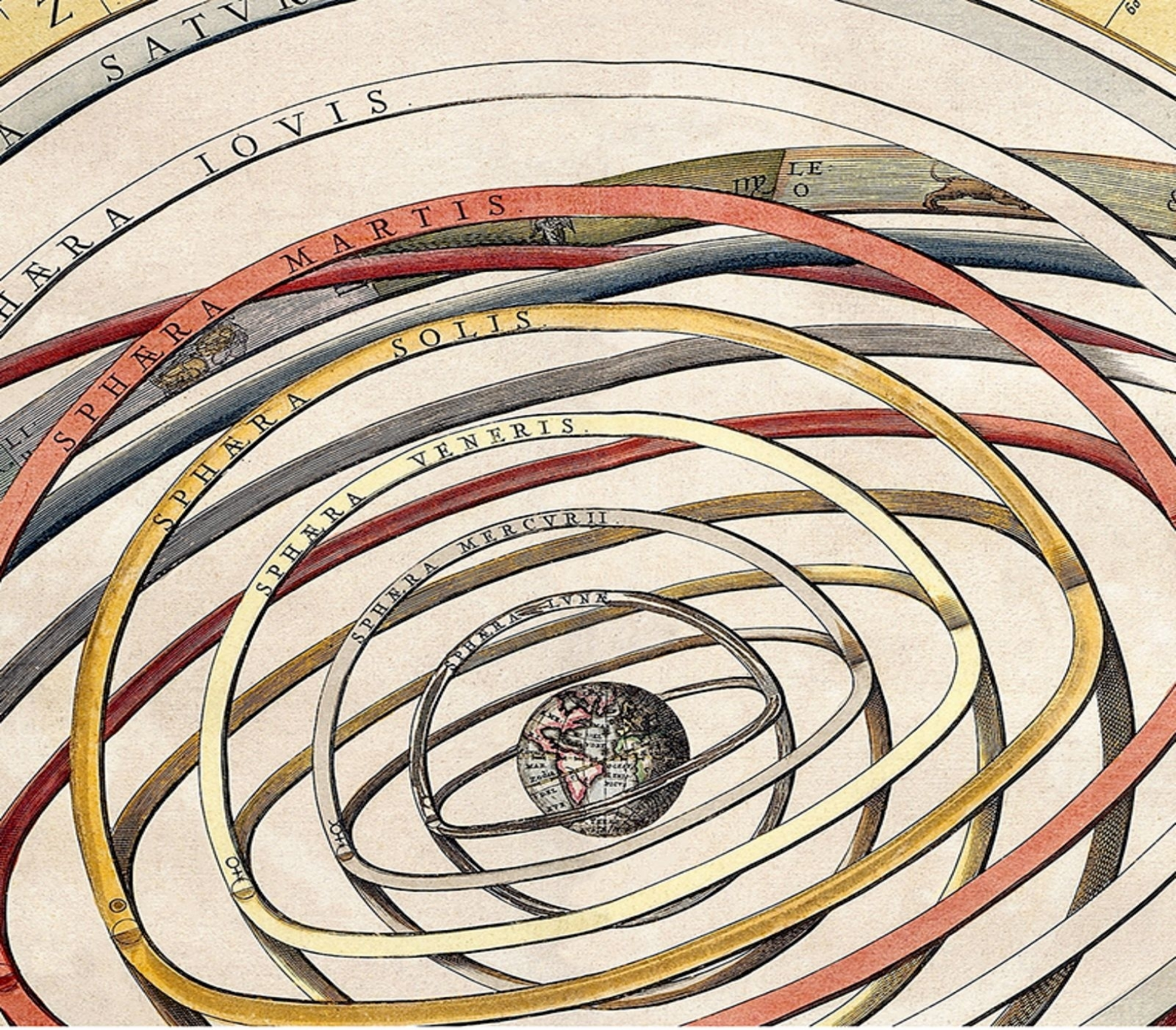

Galileo

Dialogue on the two Greatest World Systems

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DIALOGUE ON THE TWO GREATEST WORLD SYSTEMS

GALILEO GALILEI (1564–1642) is one of the most fascinating and controversial figures in the history of science. He was appointed professor of mathematics at the University of Pisa in 1589, and in 1592 he moved to the University of Padua where he taught for the next eighteen years. In 1610 he published a number of sensational telescopic discoveries, including that the lunar landscape is like that of a barren earth, and his book, the *Sidereal Message*, sold out in less than a week. The next year he was awarded the prestigious position of personal mathematician and philosopher to the Grand Duke of Tuscany in Florence. He next found that there are dark spots on the face of the sun and that gave rise to a lively international controversy that is recorded in his *Letters on the Sunspots*. He argued for a non-literal interpretation of the Bible, and he became involved in a dispute over the nature of comets with a Jesuit professor whom he lampooned in a witty essay, *The Assayer*. When the Roman Inquisition banned the Copernican theory in 1616, he refrained from writing about the motion of the Earth until a Florentine friend became Pope Urban VIII in 1623. His *Dialogue on the Two Chief World Systems*, which is not only a scientific masterpiece but an outstanding literary work, appeared in 1632. Summoned to Rome he was put on trial and condemned to house arrest in 1633. He nonetheless went on to write his *Discourse on Two New Sciences*, the work for which he is remembered as the forerunner of Newton. He died in Florence in 1642.

WILLIAM R. SHEA was Galileo Professor of History of Science at the University of Padua where Galileo taught for eighteen years. He has written extensively on the Scientific Revolution of the seventeenth century, and is currently working on a biography of Galileo.

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GALILEO GALILEI

Dialogue on theTwo Greatest World Systems, the Ptolemaic and the Copernican

Translated by
MARK DAVIE

With an Introduction and Notes by
WILLIAM R. SHEA

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CONTENTS

Introduction

Note on the Text and Translation

Select Bibliography

A Chronology of Galileo

Dialogue on the Two Greatest World Systems

- Dedication
- To the Discerning Reader
- First Day
- Second Day
- Third Day
- Fourth Day

Explanatory Notes

Index

INTRODUCTION

GALILEO GALILEI was born in Pisa on 16 February 1564,[1] the eldest son of Vincenzio Galilei and Giulia Ammannati. His father was a musician and the author of an influential *Dialogue on Ancient and Modern Music* that contains a fierce attack on his former master, Gioseffo Zarlino, and shows a gift for polemics that his son was to display in his own writings. The Galilei were an old Florentine family, and Galileo's great-great-granduncle, also named Galileo Galilei, was a famous physician who had been twice elected officer of the Governing Body of Florence and, in 1445, filled the high office of Minister of Justice. Galileo was proud of his ancestry and he described himself as a 'noble Florentine' on the title page of his first printed book, a handbook that appeared in 1606 on how to use a geometrical and military compass that he had invented.

Vincenzio Galileo had settled in Pisa when he married in 1562 but the family moved to Florence in 1574. In 1580 his son returned to Pisa to attend the University. At the time philosophy and science were still deeply influenced by the writings of the fourth-century BC Greek philosopher Aristotle, whose works were rediscovered in the Middle Ages. Aristotle maintained that things on Earth were made of four basic elements (earth, fire, air, and water) that were mixed in ever-changing proportions. He thought, however, that celestial bodies were made of an entirely different kind of material, which was unchangeable, or to use the old expression 'incorruptible'. This physics was well adapted to the concept that the Earth is at rest, and it was seen as compatible with Christian theology. Young men studying for the priesthood were expected to grasp the main lines of Aristotelian cosmology. This did not hinder the development of observational astronomy or mathematics, to which the Jesuits, a religious teaching order founded in 1534, made significant contributions.

First Steps in an Academic Career

Galileo attended the University of Pisa for four and a half years, but he left before getting his degree. This practice was not uncommon, and it was not held against him when he later applied for a university post. For a short time Galileo attended the Drawing Academy in Florence where he studied with Ostilio Ricci, who taught not only painting and design but also perspective and geometry. Galileo displayed considerable proficiency and soon composed a short treatise, *The Little Balance*, in which he reconstructed the reasoning that he believed had led the Greek scientist Archimedes to devise a way of detecting whether a goldsmith had substituted a baser metal for gold in a crown that he had fashioned for King Hero, the ruler of Syracuse. Galileo went on to tackle problems related to the determination of the centre of gravity of solids, a hot topic in mathematics and physics at the time. His results were highly praised and he was appointed professor of mathematics at the University of Pisa in 1589. Three years later he left for the more prestigious Chair of Mathematics at the University of Padua. The number of faculty members in universities was small in the sixteenth century, and Galileo was acquainted with all his colleagues. There were only forty-seven of them, and Galileo was the only one to teach mathematics, astronomy, and physics. His duties were light: he had to give no more than sixty lectures per year. His classes were attended mainly by medical students who wanted to learn how to make horoscopes for their eventual patients. Without these students, Galileo would have had an empty classroom, as we know from the formal protest he lodged when Annibale Bimbiolo, a professor of medicine, decided to give his course at 3.00 p.m., the time that Galileo had chosen because no one else taught at that hour. Outside the university, he gave private lectures on fortifications and military engineering to young noblemen bent on a military career. As was not uncommon for professors, he also rented a large house and let out rooms to rich foreign students. Galileo supplemented his income by manufacturing and selling a mathematical instrument, a forerunner of the slide-rule, which he called the military and geometrical compass. Sales of

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Galileo's compass went on apace and in 1606 he wrote an Italian handbook for users.

The first indication of Galileo's commitment to heliocentrism dates from 1597. In August of that year, he received a book by the German astronomer Johann Kepler, who argued that Copernicus had been right.[2] After reading the preface, Galileo wrote back to voice his long-standing sympathies for the view that the Earth is in motion, but also to express his fear of making his position known to the public at large.[3] When Galileo read Kepler more carefully, he became aware of their profound methodological differences, and he later reproached him in his *Dialogue on the Two Greatest World Systems* because he 'still listened and assented to the notion of the Moon's dominion over the water, and occult properties, and similar childish ideas'.[4] This statement refers to Kepler's belief that the tides are caused by the Moon, a phenomenon that Galileo thought he could explain on purely mechanical grounds as the result of the combination of the Earth's diurnal and annual revolution.

Galileo never married but his common-law wife, Marina Gamba, bore him three children: Virginia (born 13 August 1600), Livia (born 18 August 1601), and Vincenzio (born 21 August 1606). Galileo carefully cast the horoscope of all of them, something he had done for himself. The two girls were placed in a convent in Arcetri near Florence in 1614; his son Vincenzio was legitimized in 1619.

Around 1602, Galileo began making experiments with falling bodies in conjunction with his study of the pendulum. He first expressed the correct law of freely falling bodies, which says that distance travelled is proportional to the time squared, in a letter to Paolo Sarpi in 1604,[5] but he claimed to have derived it from the erroneous assumption that speed is proportional to distance whereas, as he realized later, it is proportional to the square root of the distance. In the autumn of 1604, the appearance of a particularly bright star, a supernova, revived the debate on the incorruptibility of the heavens that had been so lively a generation earlier when the Dane Tycho Brahe had argued that a very bright star, which had appeared in 1572, proved that heavenly matter was

subject to change. Galileo took his side against Aristotle in a book written in the Paduan dialect under the pseudonym of Cecco di Ronchitti. This was his first attempt to reach an audience outside university circles and poke fun at his opponents.

A New World in the Heavens: A Sidereal Message

In July 1609, while visiting friends in Venice, Galileo heard that a Dutchman had invented a device to make distant objects appear nearer and he immediately attempted to construct such an instrument himself.[6] Others were at work on similar devices, but by the end of August 1609 Galileo had managed to produce a nine-power telescope that was better than those of his rivals. He returned to Venice, where he gave a demonstration of his spying glass from the highest bell towers in the city. The practical value for sighting ships at a distance greatly impressed the Venetian authorities, who confirmed Galileo's appointment for life and raised his salary from 520 to 1,000 florins, an unprecedented sum for a professor of mathematics.

Galileo had put a convex lens at one end of a tube roughly one metre long, and a concave lens at the other end where he applied his eye. He arrived at the kind of telescope we know as the opera glass. He had the great good fortune of having access to the excellent lenses that were made on the island of Murano, just off Venice. Without the unknown and unsung craftsmen who made the lenses that he needed, Galileo would not have achieved his lasting fame as the Columbus of a new heaven. The telescope changed the way of looking at the heavens when it was used by Galileo, whose eye was prepared to see new things and whose hand was able to depict what he saw. It was not only because Galileo was a gifted and persistent observer, but also because he was an exceptional draughtsman that he was able to describe what others had failed to see or lacked the ability to record. Early in January 1610, he turned an improved version of his telescope to the skies. What he saw and reported in the *Sidereal Message*, which appeared on 13 March

1610, was to revolutionize astronomy. First, the Moon was revealed as having mountains and valleys like those on Earth. This was exciting news, because if the Moon resembled the Earth, then it might be inhabited! Second, innumerable stars popped out of the sky and untold worlds were suddenly and unexpectedly disclosed. Third, the Milky Way, which looks like a whitish cloud when seen with the naked eye, showed itself to be a mass of starlets. Fourth, the faint luminosity, which is observed on the dark side of the Moon when its illuminated part is only a thin crescent four or five days old, was correctly interpreted by Galileo, who understood that it was caused by the reflection of sunlight bouncing off the surface of the Earth. So the Moon has 'earthshine', and the reflected light that reaches it is more powerful than moonlight on Earth because the Earth is four times as big as the Moon.[7] The fifth discovery was even more spectacular: four new celestial bodies were found to orbit Jupiter, something that had never been anticipated in the wildest dreams of philosophers or astronomers. Furthermore, it enabled Galileo to name them after the Medici, the ruling family of Tuscany, the state where he was born and where he soon hoped to be recalled.

The discovery of four satellites orbiting around Jupiter was particularly important in the Copernican debate, for if Jupiter could revolve around a central body (be it the Earth or the Sun) with four attendant satellites, then it was no longer absurd to suggest that the Earth could go around the Sun with just one satellite, the Moon. If Jupiter's satellites did not prove that Copernicus was right, they removed a major obstacle to the acceptance of his theory.

While the night sky provided startling news, mundane events continued to matter. One occurred in Florence in January 1609 when the Grand Duke Ferdinand died in Florence and was succeeded by his son, Cosimo II, Galileo's former pupil. Galileo, who had been wanting to return to Florence for some time, realized that his newly-won fame might assist him in effecting a change of residence. He christened the satellites of Jupiter 'Medicean stars' in honour of the Grand Duke and his family, and he began corresponding with

Belisario Vinta, the Secretary of State. In May 1610, he formally applied and was awarded a special post with the title of 'Mathematician and Philosopher to the Grand Duke of Tuscany'.

Galileo's departure from the Venetian Republic has often caused surprise. 'Where can you find the freedom and the independence that you enjoyed in Venice?' wrote his friend Sagredo.[8] But Galileo did not see it in this light. To a Florentine correspondent he confided that a Republic made too many demands on his time, and that he could only hope to obtain the leisure needed to do his work from 'an absolute Prince'.[9]

The New Science Enters the Public Domain: The Letters on the Sunspots

The *Sidereal Message* created a sensation throughout Europe. In a characteristically generous and enthusiastic reaction, Kepler immediately hailed Galileo's achievement. Others wavered on theoretical grounds but mainly, as it seems, because their own telescopes were of poor quality. An influential Florentine nobleman, Francesco Sizzi, criticized Galileo's discoveries on astrological and hermetic grounds, but the most serious charge was made in a privately circulated manuscript written by the Florentine Ludovico delle Colombe and entitled *Against the Motion of the Earth*. It did not attack Galileo directly but ranted against Copernicans and accused them of going against Scripture. Galileo's extensive marginal notes to this tract show how incensed he was and how much he feared that he would be dragged into theological waters.

Meanwhile Galileo continued his telescopic observations in the hope of finding other satellites. The Queen of France, Marie de Médicis, who was a Florentine, wrote to say that she would be obliged if her husband, King Henry IV, could find a place in heaven. Galileo did his best, and in July 1610, he noticed that Saturn had an elongated shape. He conjectured that two satellites, one on each side of Saturn, cause this phenomenon. As was sometimes done to ensure priority without making an immediate disclosure, he sent out

an anagram of thirty-seven words to announce that he had made a new discovery. No one worked out the meaning of the anagram, and Giuliano de' Medici, the Tuscan Ambassador in Prague, was charged by the Emperor Rudolph II to ask for the solution. Galileo then officially announced that Saturn had two satellites. Unfortunately, the two objects decreased in size and, at the close of 1612, vanished altogether. Were all of Galileo's celestial discoveries to suffer such a fate? Genuinely embarrassed but still capable of mocking his own discomfiture, Galileo wrote to a friend on 1 December 1612: 'Has Saturn devoured its children? Or was their original appearance an illusion produced by the lenses, which deceived me for so long, as well as the many others who observed it with me on many occasions?'[10] What Galileo had seen were the rings of Saturn that are sometimes seen edgewise, when they are hard to detect, and sometimes slanted, when they can be identified with a better telescope than the one Galileo had, something that was done many years later by the Dutch scientist Christiaan Huygens.

Galileo's telescope was powerful enough, however, to enable him to make another discovery that was both sensational and, this time, genuine, namely that Venus has phases, not unlike the Moon. This had to be so if Venus went around the Sun, but the phases cannot be seen with the naked eye. Galileo felt the need to double-check, and once again he protected his priority claim by sending an anagram to Giuliano de' Medici in Prague on 13 November 1610. Six weeks later he had convinced himself that he had been right, and on 1 January 1611 he gave the solution of the riddle and disclosed that Venus had phases and undoubtedly went around the Sun.[11]

The Jesuits in Rome confirmed Galileo's observations, and when he returned to the Eternal City in the spring of 1611, they gave him the equivalent of an honorary doctorate in a ceremony that included no less than three cardinals. The young Prince Federico Cesi, who was in attendance, immediately asked Galileo to join the prestigious Lincean Academy that he had founded. Everyone in Rome wanted to see the new sky for himself or herself, and Galileo was frequently invited to display the marvels of his telescope in the stately gardens

of the most important Roman families. His success was so impressive that Cardinal Francesco Maria del Monte wrote to the Grand Duke Cosimo II in Florence: 'If we were still living under the ancient Roman republic, I am certain that a statue would have been erected to him on the Capitoline.'[12]

In the summer of 1611, friends met at the villa of Filippo Salviati at Le Selve near Florence. Galileo suffered from a number of physical complaints, which he blamed on the air of Florence, and he welcomed the opportunity to go to Salviati's country house. He was present when a discussion arose on the qualities of hot and cold and, specifically, why ice is lighter than water since the action of cold is to condense not rarefy. This led to a debate over the cause of floating bodies in general, with Galileo maintaining, along Archimedean lines, that the cause of floating was the relative density, whereas an Aristotelian opponent held that it was the shape. Shortly thereafter, Cardinal Maffeo Barberini (the future Pope Urban VIII) and Cardinal Ferdinando Gonzaga happened to be in Florence, and the Grand Duke invited Galileo and the Aristotelian philosopher to repeat their arguments before the distinguished visitors. Cardinal Barberini not only enjoyed the discussion but also sided with Galileo, and the two men became friends. Unfortunately, they were later to clash over the issue of Copernicanism, as we shall see.

In the autumn of 1611, Christoph Scheiner, a Jesuit professor at the University of Ingolstadt in southern Germany, made a number of observations of sunspots and was eager to make them known. He had a friend and patron in the person of Mark Welser, a wealthy merchant in Augsburg and an enthusiastic amateur of science, and he sent him three letters in which he described his findings. Welser had these letters printed and sent copies abroad, notably to Galileo and members of the Lincean Academy. As Scheiner was forbidden to use his name, lest he be mistaken and bring discredit on the Society of Jesus, he had concealed his identity under a pseudonym.[13] Galileo, however, identified him and, in two letters to Welser, took him to task for suggesting that the spots were small satellites orbiting around the Sun. Scheiner then wrote a reply that he entitled

A More Accurate Discussion of Sunspots and the Stars that Move around Jupiter, and Galileo retorted with a third letter to Welser in December 1612 in which he declared that he had observed the sunspots before Scheiner. In an age when scientists were hypersensitive about priorities, this did not endear him to his rival. It also opened a breach between Galileo and the Jesuits. Galileo's three letters were published in Rome the following year, under the auspices of the Lincean Academy.[14] Since planets had been mentioned in his *Letters on the Sunspots* Galileo had been able to bring up the matter of the Copernican system and, for the first time, to endorse it unequivocally in print.

Science and the Bible

Meanwhile the problem of Copernicanism did not lie dormant in Florence. In November 1612, Galileo heard that a well-known Dominican friar, Niccolò Lorini, had criticized the heliocentric theory. When asked for an explanation, he replied that he had meant no harm. When the motion of the Earth had been mentioned in a discussion he had said, 'a few words just to show I was alive. I said, as I still say, that this opinion of Ipernicus—or whatever his name is—would appear to be hostile to Divine Scripture.'[15] Lorini's ignorance of the very spelling of Copernicus's name makes it unlikely that he had much interest in astronomy, and it is a pity that after attacking the Jesuits, Galileo should have been led to antagonize the Dominicans. But things were to get worse. On 12 December 1613, objections were raised, on Scriptural grounds, against the notion that the Earth was a planet, at a dinner the Grand Duke gave in Pisa. Galileo was absent but his friend and former pupil, Benedetto Castelli, defended the Copernican theory when he was asked about it by Christina of Lorraine, the mother of the Grand Duke. A couple of days later Castelli wrote to Galileo to inform him that he had behaved as gallantly as a knight, but Galileo felt that the battle could not be entrusted to such an inexperienced defender. He immediately sent Castelli a letter in which he argued that the motion of the Earth

was not at variance with the Bible.[16] Peace seemed restored, but a year later, in 1614, another Dominican, Tommaso Caccini, preached an inflammatory sermon against the Copernican system from the pulpit of Santa Maria Novella in Florence on 21 December, the Fourth Sunday of Advent. News of his outburst soon reached Rome, and Galileo's friend, Monsignor Giovanni Ciampoli, raised the matter with Cardinal Barberini, the future Urban VIII, who urged 'greater caution in not going beyond the arguments used by Ptolemy and Copernicus', as Ciampoli told Galileo in a letter. Ciampoli went on to explain that great care should be exercised because someone might claim that the telescope provided evidence for life on the Moon, and this could lead to someone else asking if the lunar inhabitants 'were descended from Adam or how they came out of Noah's ark'. It was wise, therefore, 'to declare frequently that one placed oneself under the authority of those who have jurisdiction over the minds of men in the interpretation of Scripture'.[17]

Not to be outdone by Caccini, the Dominican Niccolò Lorini forwarded a copy of Galileo's *Letter to Castelli* to the Inquisition in Rome, and in order to cope with this new challenge Galileo expanded his *Letter to Castelli* into the *Letter to the Grand Duchess Christina*, which contains his most detailed pronouncement on the relations between science and Scripture.[18] Borrowing the *bon mot* of Cardinal Cesare Baronio, 'the intention of the Holy Spirit is to teach us how to go to heaven, not how the heavens go',[19] Galileo stressed that God speaks through the Book of Nature as well as the Book of Scripture, and that care must be exercised lest metaphorical expressions in the Bible be interpreted as scientific facts.

Further complications arose from the publication early in 1615 of a book by Paolo Antonio Foscarini, a Carmelite monk, who also wanted to defend Copernicanism from the charge that it was at variance with what the Bible taught. Foscarini sent a copy of his book to Cardinal Robert Bellarmine, requesting his opinion. The Cardinal's reply was friendly but firm: 'It seems to me that both you and signor Galileo are acting prudently in confining yourselves to speaking hypothetically and not in absolute terms', and he added

that 'to demonstrate that the appearances are saved by the hypothesis that the Sun is at the centre and the Earth is in the heavens, is not the same as demonstrating that the Sun really is at the centre and the Earth in the heavens. I believe that the first can be demonstrated, but I have very great doubts about the second.'[20] Bellarmine admitted that should such a proof become available then Scripture would have to be reinterpreted with the utmost care.

A copy of the Cardinal's letter was sent to Galileo, who was not unduly troubled because he believed that he had just such a proof. This was his clever (but unfortunately wrong) theory that the tides would not occur if the Earth were not in motion. This theory eventually became the subject of the Fourth Day of the *Dialogue on the Two Greatest World Systems*, which he had originally entitled *A Discourse on the Tides*. Armed with this argument, which he believed to be decisive, Galileo marched off to Rome at the end of 1615. He talked to all and sundry about his proof, but the only result was that he got the Holy Office of the Inquisition to take the heliocentric theory seriously, something they had not done before. The eleven theological experts who acted as consultants to the Holy Office were asked on 19 February 1616 to examine the two following propositions: (1) The Sun is at the centre of the world and hence completely motionless, and (2) The Earth is not the centre of the world and motionless but moves as a whole and also with diurnal motion. Five days later they unanimously condemned the first proposition as 'foolish and absurd in philosophy, and formally heretical since it explicitly contradicts sentences found in many places in Sacred Scripture according to the proper meaning of the words and according to the common interpretation and understanding of the Holy Fathers and of learned theologians'. The second proposition received the 'same censure in philosophy' and, with respect to theology, was considered 'at least erroneous'.[21] Their report was approved by the Pope and the members of the Holy Office on 25 February and the next day, acting on the orders of Pope Paul V, Cardinal Bellarmine informed Galileo that he had to abandon the Copernican theory, and stop teaching it orally or in writing.

As was current practice, the ruling of the Holy Office was passed to the Congregation of the Index, which was in charge of censoring books, and on 5 March, Copernicus's *On the Revolution of the Heavenly Spheres* was proscribed 'until revised' and Foscarini's book banned outright. Galileo himself was not mentioned but he was worried and, before he left Rome, he called on Cardinal Bellarmine on 26 May to inform him that it was rumoured in Florence that he had been condemned by the Inquisition. The Cardinal gave him a certificate in which it is stated that he had not been condemned but merely informed of the decision of the Congregation of the Index. Galileo kept this precious document, which he showed to no one.

The Problem of Longitude at Sea and the Quarrel over Comets in The Assayer

Upon his return to Florence Galileo applied himself to a much discussed but non-controversial topic: the determination of longitudes at sea. He hoped that accurate tables of the periods of revolutions of the satellites of Jupiter would enable him to predict how their relative positions would appear from any point on earth, and hence allow seamen to know their location merely by looking through the telescope. The method was sound and it kept Galileo busy over a long period of time but it could not be used because of the practical difficulties of applying it on a ship at sea.

In the autumn of 1618 great excitement was generated over the appearance, in rapid succession, of three comets. Galileo was bedridden at the time and unable to make observations. He was nonetheless asked to comment on accounts given by others, and he chose to attack a lecture delivered by Orazio Grassi, the Jesuit professor of mathematics at the Roman College, who had located the comet beyond the Moon, as we do today. This irked Galileo, for he approached the problem from a very different standpoint since he thought that comets were merely optical phenomena caused by refraction in atmospheric vapour or in the clouds. He set out this view, which caused surprise since it had been that of Aristotle in

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